ARMY RESEARCH LABORATORY

Shock Experiment Results of the DFuze 8-Channel Inertial Sensor Suite That Contains Commercial Magnetometers and Accelerometers

Bradford S. Davis
Michael B. Hamilton
David J. Hepner

ARL-MR-532 **April 2002**

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-MR-532 April 2002

Shock Experiment Results of the DFuze 8-Channel Inertial Sensor Suite That Contains Commercial Magnetometers and Accelerometers

Bradford S. Davis
David J. Hepner
Weapons and Materials Research Directorate, ARL

Michael B. Hamilton
Naval Surface Warfare Center, Dahlgren Division

Abstract

This report describes shock experiments performed on a 1.4-inch (35.56-mm) diameter double-sided board that contains an inertial sensor suite (ISS) in support of the ongoing U.S. Army Research Laboratory diagnostic fuze (DFuze). The DFuze represents a high-g projectile-borne measurement system for obtaining in-bore and in-flight ballistic data that significantly contribute toward the design, development, failure diagnostics, and aerodynamics determination of artillery or other projectiles. The ISS uses several commercial off-the-shelf micro-electro-mechanical systems accelerometers, magnetometers, and optical sensors used for determining estimates of the projectile's body orientation, axial acceleration, radial acceleration, and roll rate. During the ground experiments, ISS boards were encapsulated within a specially designed fixture and shocked while powered in various orientations to simulate high-g set-back, set-forward, and balloting launch conditions. Post-shock performance of each sensor was then obtained to determine bias offset, scale factor errors, and shock survivability. The shock experiments were performed on a high velocity and acceleration shock machine at Aberdeen Proving Ground, Maryland. As a result of these experiments, the ISS boards have been g-qualified to at least a 19-kg launch acceleration while powered. The ISS boards will be used in ongoing DFuze flight experiments in support of the following Navy and Army developmental projectile programs: Extended Range Guided Munitions, Advanced Gun System, Autonomous Naval Support Round, XM982 Excaliber, and Tank Extended Range Munition Kinetic Energy XM1007. To date, 30 ISS boards have been flight tested without any failures.

ACKNOWLEDGMENTS

The authors would like to thank each person by name who supported the inertial sensor suite (ISS) board shock experiments. Mr. Charles Mitchell, formerly of Dynamic Sciences Incorporated (DSI), is greatly appreciated for fabricating the shock experiment fixtures. Mr. Rex Hall, of Geo-Centers, is thanked for his schematic capture work and board layout support during the design of the inertial sensor suite in conjunction with National Aeronautics and Space Administration (NASA) Wallops Island and the NASA sounding rocket operations contract. Mr. Edward Bukowski, of DSI, Mr. Nathaniel Hundley, of DSI, and James Spangler, of the U.S. Army Research Laboratory, are all thanked for their technical support which included population and encapsulation of the ISS boards. Mr. Robert Solouff, of Analog Devices, is also thanked for supplying the ADXL78 and ADXL278 accelerometers before they were released for commercial sale.

INTENTIONALLY LEFT BLANK

Contents

Figures

Tables

SHOCK EXPERIMENT RESULTS OF THE DFUZE 8-CHANNEL INERTIAL SENSOR SUITE THAT CONTAINS COMMERCIAL MAGNETOMETERS AND ACCELEROMETERS

1. Introduction

Recent high-g shock experiments were performed on the inertial sensor suite (ISS) of the diagnostic fuze (DFuze) by the Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, Maryland, with support from a guest researcher from the Naval Surface Warfare Center (NSWC), Dahlgren Division. DFuze is a patented (US6349652) high-g projectile-borne measurement system for obtaining in-bore and in-flight ballistic data (i.e., accelerations, angular rates, and angular orientations) that significantly contribute toward the design, development, failure diagnostics, and aerodynamics determination of artillery or other projectiles. The DFuze predecessors have been providing critical measurement data that have immensely helped many Army programs such as Sense and Destroy Armor **[1]**. DFuze is comprised of g-qualified miniature sensors, microelectronics, signal and power-conditioning printed circuit boards (PCBs), on-board data acquisition, telemetry components, mechanical hardware, and a power supply as described by Hepner and Borgen **[2]**. As technology improves, smaller, more robust, and higher performance DFuze components replace the older ones. These components come from the commercial sector, ARL's internal research and development, and from specialized development programs such as the tri-service Hardened Subminiature Telemetry and Sensor System program sponsored by the Army's Simulation Training and Instrumentation Command **[3, 4, 5]**.

The latest version of the ISS board is a two-sided 1.4-inch (35.56-mm) diameter PCB (see Figure 1) that contains commercial off-the-shelf (COTS) micro-electro-mechanical systems (MEMS) and other sensors for obtaining in-flight ballistic data. The sensors include a Honeywell HMC1023 three-axis magnetometer for determining body orientation relative to the earth's magnetic field, a Silicon Designs SDI1210 single-axis accelerometer for determining body-fixed axial acceleration along the trajectory, an Analog Devices ADXL250 or ADXL278 dual-axis accelerometer for determining body-fixed radial acceleration, four Analog Devices ADXL78 single-axis accelerometers used as an accelerometer only (AO) ring for determining body-fixed roll rate, and an Analog Devices AD22100SR temperature sensor used for temperature compensation of the inertial measurement unit. Four ARL-patented solar likeness indicating transducer (SLIT) optical sensors are part of the DFuze sensor suite but only the signal conditioning is situated on the ISS board. The SLIT sensors are situated on the DFuze's exterior and are further described in Hepner, Hollis, and Mitchell **[6]**. The processed solar data provide body orientation relative to the sun. A body-fixed coordinate system (I, J, and K) was assigned to the ISS board as displayed in Figure 1 (+I direction means positive axial

acceleration, +J direction means positive radial acceleration, and +K means positive radial acceleration 90 degrees counterclockwise from +J axis).

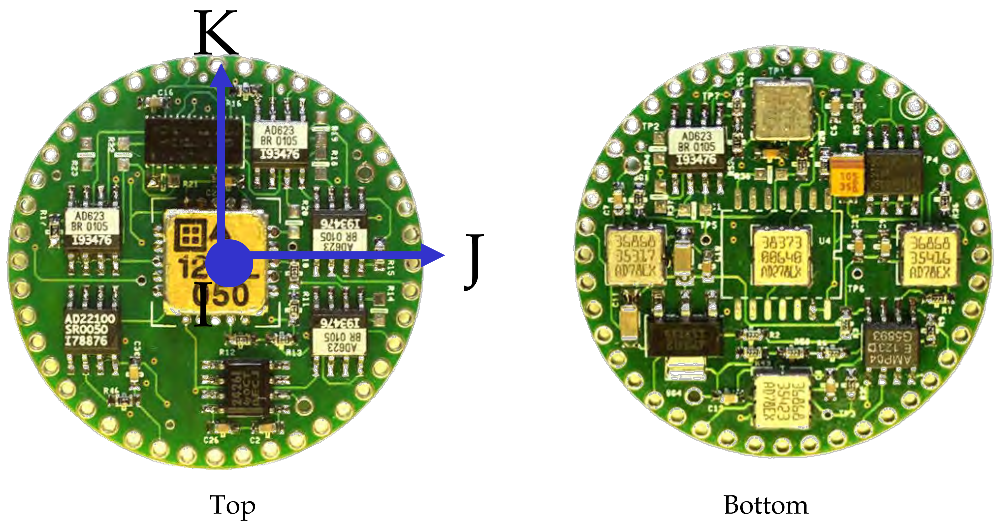

Figure 1. DFuze ISS Board.

Within the DFuze, the ISS board is oriented so that the components on top of the board experience g-loading into the board and those components on the bottom experience g-loading away from the board during launch (see Figure 2). The ISS board is situated within an aluminum body, approximately 3.6 inches (91.44 mm) from the nose tip. Shock experiments were arranged so that the individual sensor components could be qualified for their ability to survive artillery level gun launch. For example, the Navy's Extended Range Guided Munition (ERGM) has a maximum set-back acceleration level of 12,500 g (in which g = the acceleration of gravity). Balloting loads are typically 10% of set-back loads, and set-forward loads are typically 20% of set-back levels. This report describes how the experiments were performed and presents the results.

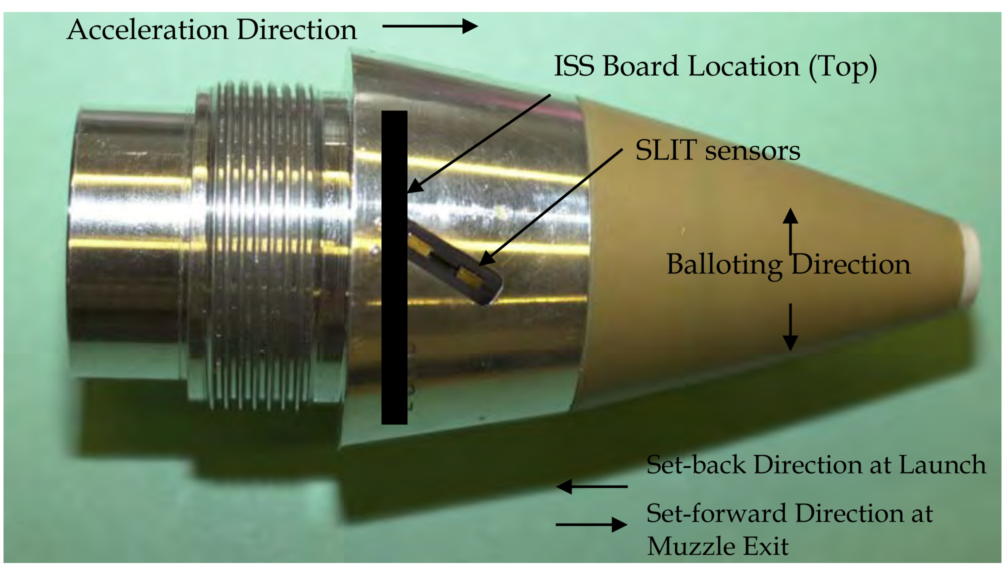

Figure 2. DFuze Showing ISS Board Orientation Relative to Launch Conditions.

2. DFuze ISS Board Shock Experiment

The shock experimentation of the new DFuze ISS board was performed to determine the survivability and post-shock performance of the sensors and associated electronics to a simulated gun launch while the sensors were powered during the shock event. It is important to note that the artillery-level shock experimentation will far exceed the maximum recommended shock acceleration as specified by each sensor's manufacturer for survivability. Davis, Brown, Myers, and Hollis **[7]** had g-qualified several COTS MEMS sensors during ground and flight experiments for earlier versions of the ISS board. A specially designed experimental fixture, as seen in Figure 3, was fabricated to allow the sensor package to be mounted in any of three different orientations. The three orientations thus allowed shock experimentation with the top of the board facing up (orientation in which the board will experience a set-back load), bottom of the board facing up (orientation in which the board will experience a set-forward load), and top of the board facing horizontal (orientation in which the board will experience a balloting load).

In preparation for the shock experiments, a single ISS board was wired so that it could be externally powered and each individual sensor could be monitored via its own color-coded wire. The ISS board was then encapsulated within the fixture, as shown in Figure 4. The fixture containing the encapsulated ISS board was then mounted on ARL's IMPAC66 high velocity and acceleration shock machine. Two of the three orientations are shown in Figures 5 and 6. The shock machine used high-pressure gas to raise or lower a drop table on command. Once the table was at the desired height, an elastic cord assisted in pulling the drop table toward an anvil that is covered with mitigation material for high-g shock simulations. Shocks as great as 30,000 g are achievable. Deceleration was measured by a reference accelerometer (PCB Piezotronics model 350-821) mounted directly on the drop table. An 8-channel analog-to-digital data acquisition system comprised of National Instruments hardware and Labview software was used to record the data. A body-fixed right-handed coordinate system (X, Y, and Z) was also established for the shock table, as displayed in Figure 7 (+X means that the sense axis of the unit undergoing test is aligned with the shock acceleration direction; +Y or +Z means that the sense axis of the unit undergoing test is perpendicular to the shock acceleration).

Figure 3. Shock Experiment Fixture.

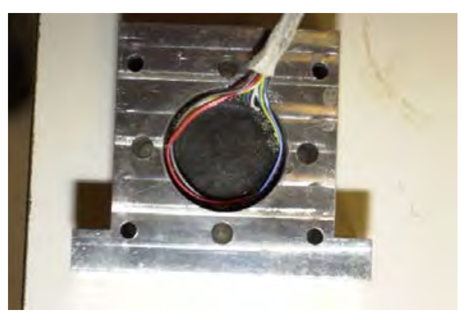

Figure 4. Encapsulated ISS Board in Fixture.

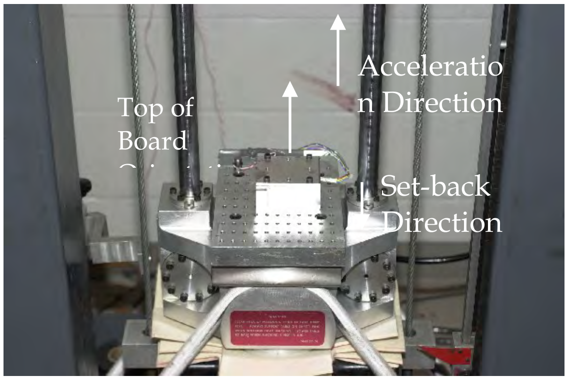

Figure 5. Set-back Orientation.

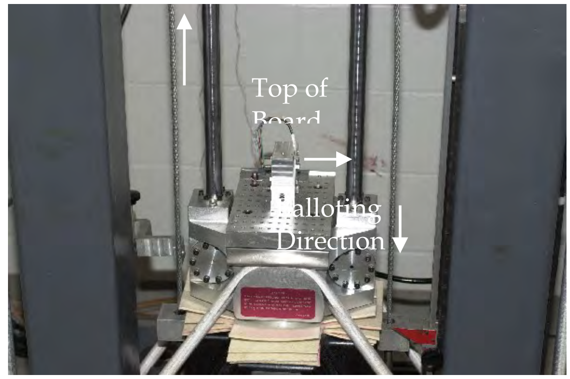

Figure 6. Balloting Orientation.

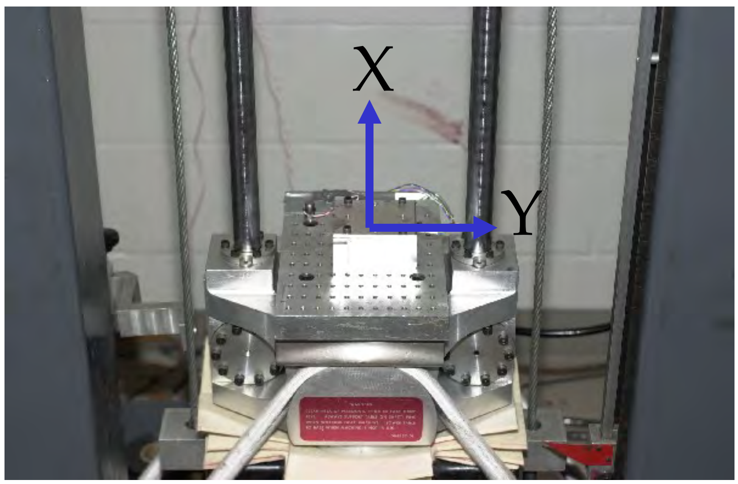

Figure 7. Shock Table Coordinate System.

3. DFuze ISS Board Shock Experiment Results

For these experiments, four felt pads, each 0.25 inch (6.35 mm) thick, were used as the mitigation material. The first shock experiment performed was in the set-back orientation at a level of 13,000 g. The shock machine was dropped at a height of 22 inches (55.9 cm) to achieve a maximum nominal 13,000-g shock magnitude with an initial pulse duration of 0.1 ms. The initial shock pulse is followed by smaller shock pulses that gradually dissipate. An example of the shock pulse waveform is shown in Figure 8 and is expanded to show more detail in Figure 9. Although typical shock pulses for artillery projectiles last between 15 and 25 ms, with an amplitude between 10,000 and 20,000 g, and have a shape resembling a half sine wave, the shock experienced by the table is a cursory evaluation and is easily performed. Our experience is that a shock table acceleration of the same magnitude as a launch acceleration is actually much harsher on the device. This is attributable to the high frequency nature of the shock. The second shock experiment performed was in the balloting orientation at a nominal level of 15,000 g. A third shock experiment was performed in the set-forward orientation at a

nominal level of 20,000 g. We achieved the set-forward orientation by mounting the fixture on its other side. The change in bias and scale factor errors of each sensor was measured before and after each shock as shown in Tables 1 through 3.

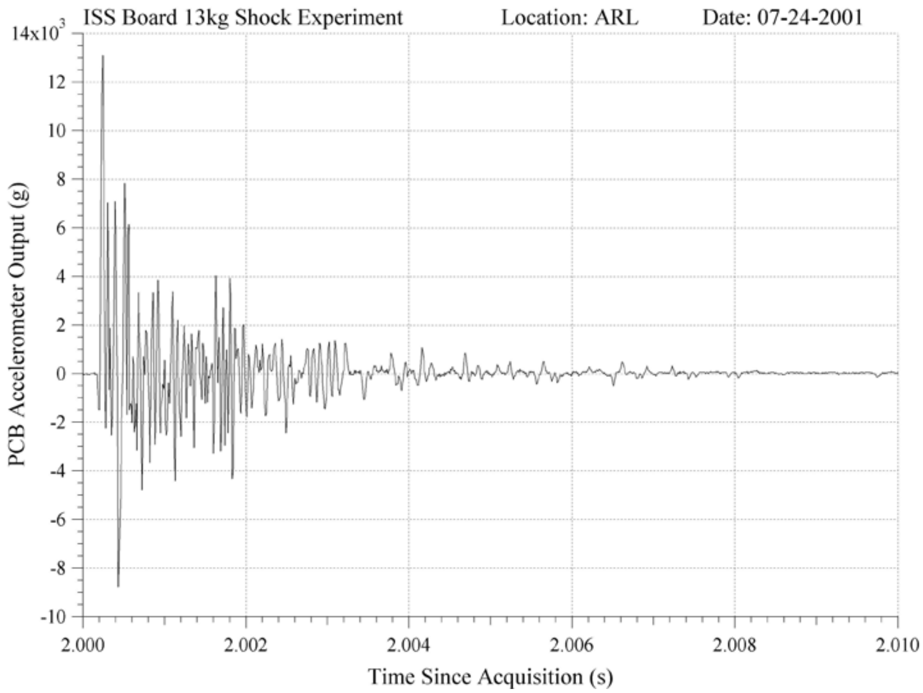

Figure 8. Shock Pulse Wave Form From 13,000-g Set-back Orientation Shock Experiment.

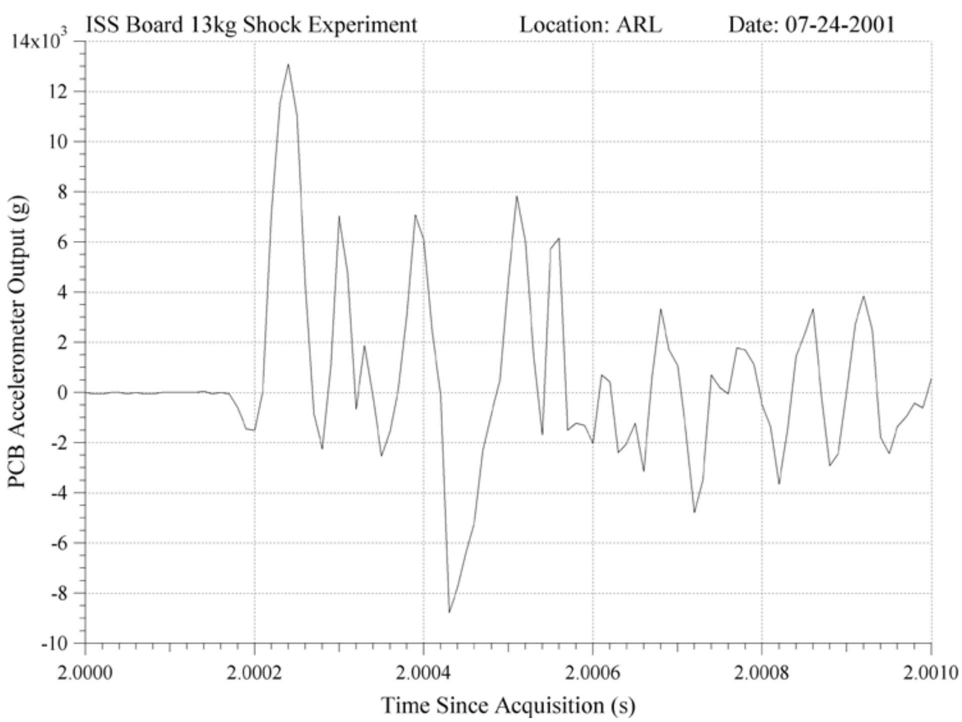

Figure 9. Expanded View of Shock Pulse Wave Form.

Table 1. 13,000-g Set-back Orientation Shock Experiment Results

Sensor	Sense Axis	Chip Orientation	Before Shock Bias (V)	After Shock Bias (V)	Before Skock Scale Factor	After Shock Scale Factor	Δ Bias	Δ Scale Factor (percent)	Comments
HMC1023	+J	Top	2.84	2.82	1.73 V/G	1.7 V/G	0.012 G	-1.76	
	+K	Top	3.41	3.46	1.94 V/G	1.92 V/G	0.026 G	-1.03	
	+I	Top	2.80	2.82	1.87 V/G	1.87 V/G	0.011 G	0	
ADXL250	-J	Bottom	2.483	2.493	35 mV/g	35 mV/g	0.286 g	0	
	+K	Bottom	2.506	2.508	35 mV/g	35 mV/g	0.057 g	0	
SDI1210	+I	Top	2.524	2.511	200 mV/g	200 mV/g	-0.065 g	0	
AO Ring		Bottom	1.004	1.007	Unknown	Unknown	0.003 V	Unknown	

Table 2. 15,000-g Balloting Orientation Shock Experiment Results

Sensor	Sense Axis	Chip Orientation	Before Shock Bias (V)	After Shock Bias (V)	Before Skock Scale Factor	After Shock Scale Factor	Δ Bias	Δ Scale Factor (percent)	Comments
HMC1023	+J	Top	2.82	2.82	1.7 V/G	1.72 V/G	0 G	1.18	
	+K	Top	3.46	3.47	1.92 V/G	1.96 V/G	0.005 G	2.5	
	+I	Top	2.82	2.81	1.87 V/G	1.87 V/G	0.005 G	0	
ADXL250	-J	Bottom	2.493	2.102	35 mV/g	35 mV/g	11.18 g	0	Large Bias Shift
	+K	Bottom	2.508	4.057	35 mV/g	Unknown		Unknown	Not Operational
SDI1210	+I	Top	2.511	2.032	200 mV/g	200 mV/g	2.395 g	0	Large Bias Shift
AO Ring		Bottom	1.007	0.553	Unknown	Unknown	0.454 V	Unknown	Bias Shift

Table 3. 20,000-g Set-Forward Orientation Shock Experiment Results

Sensor	Sense Axis	Chip Orientation	Before Shock Bias (V)	After Shock Bias (V)	Before Skock Scale Factor	After Shock Scale Factor	Δ Bias	Δ Scale Factor (percent)	Comments
HMC1023	+J	Top	2.82	2.81	1.72 V/G	1.72 V/G	0.006 G	0	
	+K	Top	3.47	3.48	1.96 V/G	1.96 V/G	0.005 G	0	
	+I	Top	2.81	2.84	1.87 V/G	1.87 V/G	0.016 G	0	
ADXL250	-J	Bottom	2.102	3.523	35 mV/g	35 mV/g	40.6 g	0	Large Bias Shift
	+K	Bottom	4.057	2.497	Unknown	35 mV/g	-44.57 g	0	Large Bias Shift
SDI1210	+I	Top	2.032	1.088	20 mV/g	200 mV/g	4.722 g	0	
AO Ring		Bottom	0.553	0.448	Unknown	Unknown	0.105 V	Unknown	

3.1 Magnetometer (HMC1023) Survivability

After each shock experiment, the bias and scale factor of each axis of the HMC1023 three-axis magnetometer was checked in a single-axis Helmholtz coil. The Helmholtz coil was able to cancel the local earth's magnetic field and to simulate a known field. The bias and scale factor, while exposed to the known magnetic field, was relatively the same before and after all shocks (see Tables 1 through 3). Since these devices are being used for measurement instrumentation purposes, small biases and scale factor errors are tolerated and can be corrected in the post-processing of the data. Therefore, since the magnetometer survived the 13,000-g set-back orientation shock, the 15,000-g balloting

shock, and the 20,000-g set-forward shock without being compromised, the magnetometer would be recommended for artillery level flight conditions.

3.2 Accelerometer (ADXL250) Survivability

Although the ADXL250 survived the 13,000-g shock in the set-back orientation without large changes in scale factor or bias, it experienced non-operation of Y-axis and a large bias shift of the X-axis during the balloting orientation shock experiment. The Y-axis was producing 4V after the 15,000-g shock event. However, the Y-axis was operational after the 20,000-g set-forward shock event and returned to its original pre-experiment bias. This anomaly in operation led to additional experimentation on this device.

For the additional experiments, two ADXL250s were mounted on two separate evaluation boards. These boards were then encapsulated into the shock fixture with one device facing up and one facing down (see Figure 10). The ADXL250s were shocked a total of eight times with shock levels that ranged from 8,000 to 22,000 g in a randomized fashion (see Table 4). Since the scale factor did not seem to be affected by shock in the previous shock data, the scale factor was not measured after each shock. Only the bias and sensor operation characteristics were measured during these additional experiments.

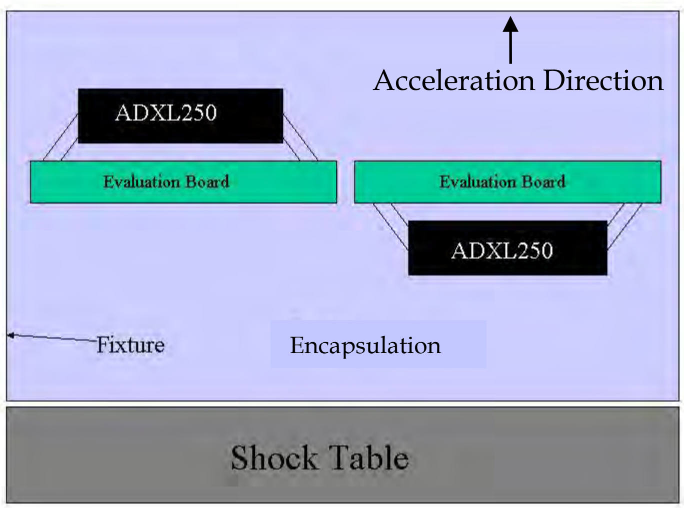

Figure 10. Sketch of ADXL250 Shock Experiment Configuration.

The ADXL250 that was on the bottom of the board and facing down still had a problem. It was intermittent in its operation, as described in Experiments 2 and 3 of Table 4, as seen in Figures 11 and 12. When oriented in this manner, the ADXL250 experienced an initial force that pulled its proof mass away from its die substrate during the set-back acceleration. An attempt to determine the cause of the non-operation was made by X-raying the ISS board. However, the only determination that could be made from the X-rays was that the solder joints to the die were still intact (see Figure 13). For a complete investigation, the sensors would need to be extracted from the encapsulation and examined under a scanning electron microscope. To date, no plans have been made

for this investigation. The ADXL250, when mounted on the top of the board and facing up, did not experience any large bias shifts or non-operation.

Table 4. ADXL250 Shock Experiment Results

Shock No.	Max Shock Level (g)	Sense Axis and Orientation	Shock Table Orientation	Before Shock Bias (V)	After Shock Bias (V)	Δ Bias (V)	Δ Bias (g)	Comments
1	13943	+K Top	+Z	2.521	2.522	-0.001	0	
		-J Top	+Y	2.351	2.351	0	0	
		-K Bottom	-Z	2.454	2.445	0.009	0	
		+J Bottom	-Y	2.493	2.503	-0.01	0	
2	18920	+K Top	+Z	2.521	2.542	-0.021	-0.52	
		-J Top	+Y	2.351	2.351	0.000	0	
		-K Bottom	-Z	2.445	0.087	2.358		Not Operational
		+J Bottom	-Y	2.503	2.505	-0.002	-0.05	
3	21040	+K Top	+Z	2.54	2.524	0.016	0.40	
		-J Top	+Y	2.35	2.352	-0.002	-0.05	
		-K Bottom	-Z	0.087	2.504	-2.417	-60.43	Operational
		+J Bottom	-Y	2.505	2.507	-0.002	-0.05	
4	17042	+K Top	+Z	2.526	2.526	0	0	
		-J Top	+Y	2.352	2.351	0.001	0.02	
		-K Bottom	-Z	2.458	2.457	0.001	0.03	
		+J Bottom	-Y	2.508	2.507	0.001	0.02	
5	20046	+K Top	+Z	2.527	2.520	0.007	0.18	
		-J Top	+Y	2.351	2.351	0	0	
		-K Bottom	-Z	2.452	2.755	-0.303	-7.58	Large Bias Shift
		+J Bottom	-Y	2.507	2.509	-0.002	-0.05	
6	21549	+K Top	+Z	2.521	2.507	0.014	0.35	
		-J Top	+Y	2.351	2.351	0	0	
		-K Bottom	-Z	2.755	4.963	-2.208		Not Operational
		+J Bottom	-Y	2.509	0.077	2.432		Not Operational
7	8075	+K Top	+Z	2.507	2.507	0	0	
		-J Top	+Y	2.351	2.351	0	0	
		-K Bottom	-Z	4.952	4.952	0		Not Operational
		+J Bottom	-Y	0.076	0.076	0		Not Operational
8	13755	+K Top	+Z	2.507	2.536	-0.029	-0.72	
		-J Top	+Y	2.351	2.349	0.002	0.05	
		-K Bottom	-Z	4.952	0.087	4.865		Not Operational
		+J Bottom	-Y	0.076	2.499	-2.423	-60.58	Operational

3.3 Accelerometer (ADXL78) Survivability

The four Analog Devices ADXL78 single-axis accelerometers representing the AO ring were also facing down (experiencing an initial force that pulled the proof mass away from the die substrate) in the 13,000-g set-back orientation shock experiment. These accelerometers survived the set-back orientation shock with no problems (see Table 1). In the balloting orientation, the AO ring experienced a 0.454-V bias shift (see Table 2). In the set-forward shock experiment, the bias shifted 0.105 V (see Table 3). Although the

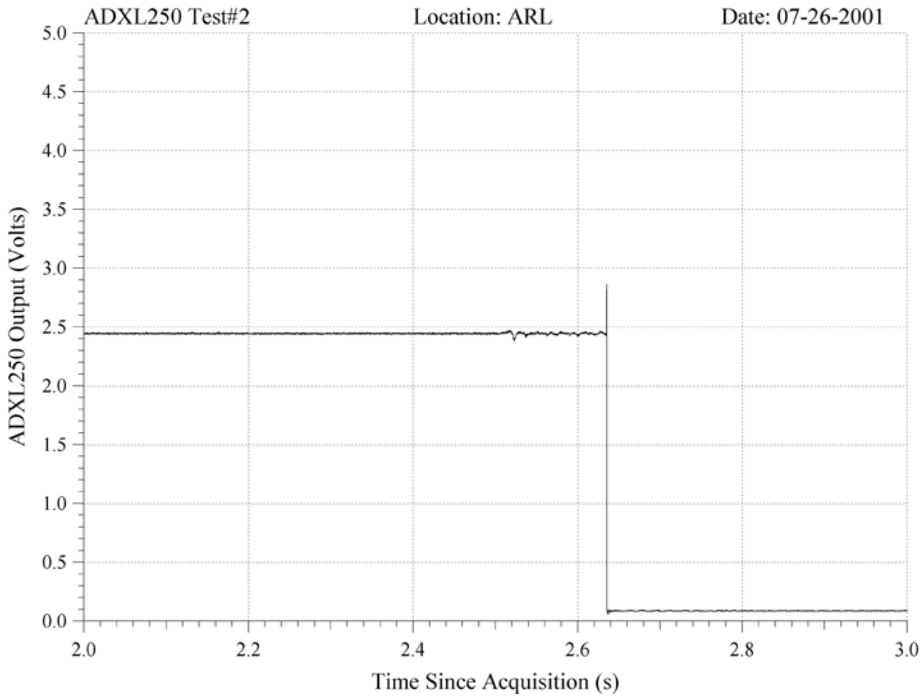

Figure 11. ADXL250 Output (-K-axis bottom) During Shock Experiment No. 2.

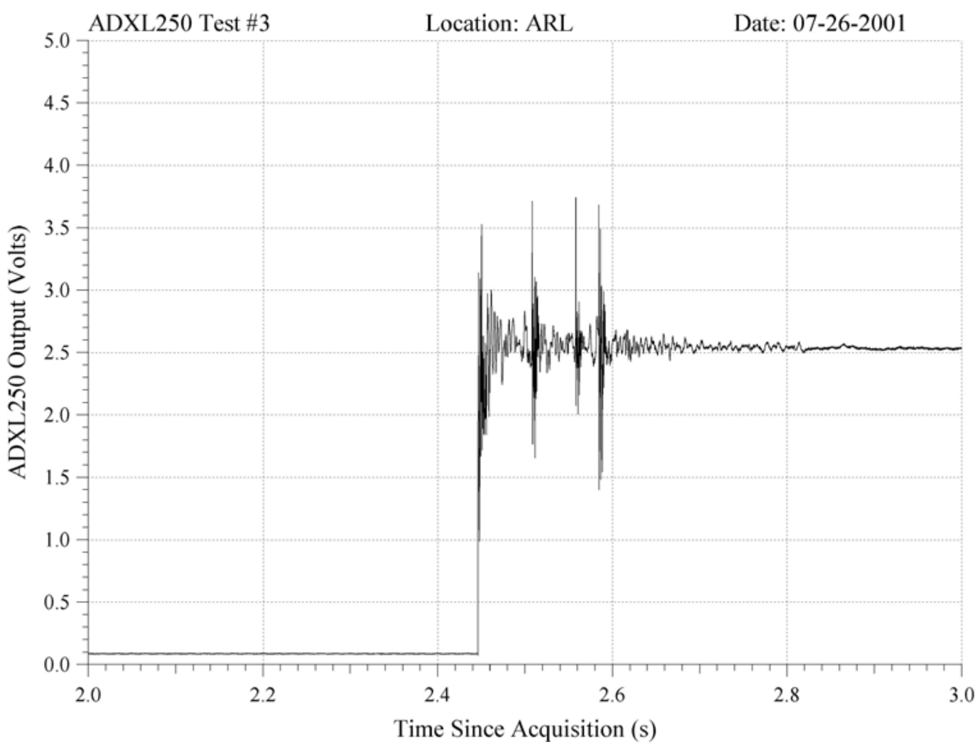

Figure 12. ADXL250 Output (-K-axis bottom) During Shock Experiment No. 3.

scale factor was not determined after each test, the AO ring was exercised for functionality. It functioned after each experiment. It was determined that since the 15,000-g balloting shock was much greater than would ever be seen in actual artillery-level flight conditions.

3.4 Accelerometer (SDI1210) Survivability

The Silicon Devices SDI1210 single-axis accelerometer seemed to survive the 13,000-g set-back shock event (see Table 1). The sensor did have problems handling the 15,000-g balloting and 20,000-g set-forward shock events (see Tables 2 and 3). The 20,000-g set-forward shock event is much higher than would be seen in normal gun firings. The purpose of the experiment in this orientation was to determine if the board could be installed in the opposite direction (so that the top became the bottom and vice versa) for future flight experiments. Since the SDI1210 also had problems in the set-forward orientation, further experimenting was performed. The additional experimentation is discussed in the next section.

3.5 Accelerometer (ADXL278 and SDI1210) Survivability

Since the ADXL250 experienced anomalies when oriented upside down, experiments were planned to see if the ADXL278 could be used as its replacement or if the ISS board could be flipped. For these experiments, two ISS boards were used with an ADXL278 and a SDI1210 mounted on each board. These boards were then wired and encapsulated inside the fixture, with one ADXL278 and one SDI1210 pointing up and one each facing down (see Figure 14). The fixture was then mounted onto the drop table and shocked a total of seven times (five times in the set-back orientation and two times in the balloting orientation) with increasing shock levels. Tables 5 and 6 show the tabulated results of these shock experiments for the SDI1210 and ADXL278. Since the scale factor did not seem to be affected by the shock in the previous experiments, the scale factor was not measured after each shock. Therefore, the sensor bias and operation were the only characteristics measured during these additional experiments.

The SDI1210 single-axis accelerometer survived the initial 19,000-g shock when it was oriented on the top and on the bottom of the ISS board. Upon subsequent shock experiments, a large bias shift occurred for the SDI1210 mounted on the bottom of the board and then to the SDI1210 mounted on top of the board until both devices were no longer operational. The accelerometer facing downward experienced a small bias shift after the second shock experiment (see Figure 15), a large bias shift after the third shock experiment (see Figure 16), and completely failed after the fourth shock experiment (see Figure 17). The accelerometer on top of the ISS board had a large bias shift after the fourth shock experiment and failed completely after the fifth shock experiment. No data were obtained for the accelerometers in the balloting orientation since both were no longer operational during Experiments 6 and 7.

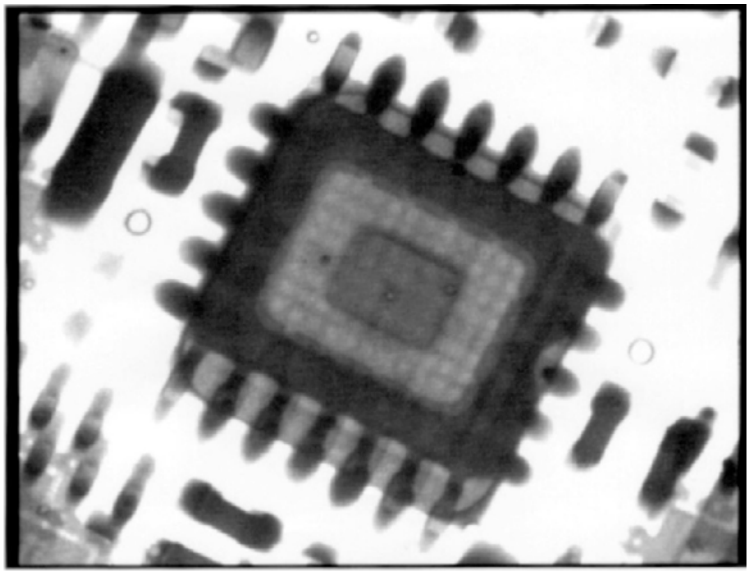

Figure 13. X-ray of ADXL250 After All Shock Experiments.

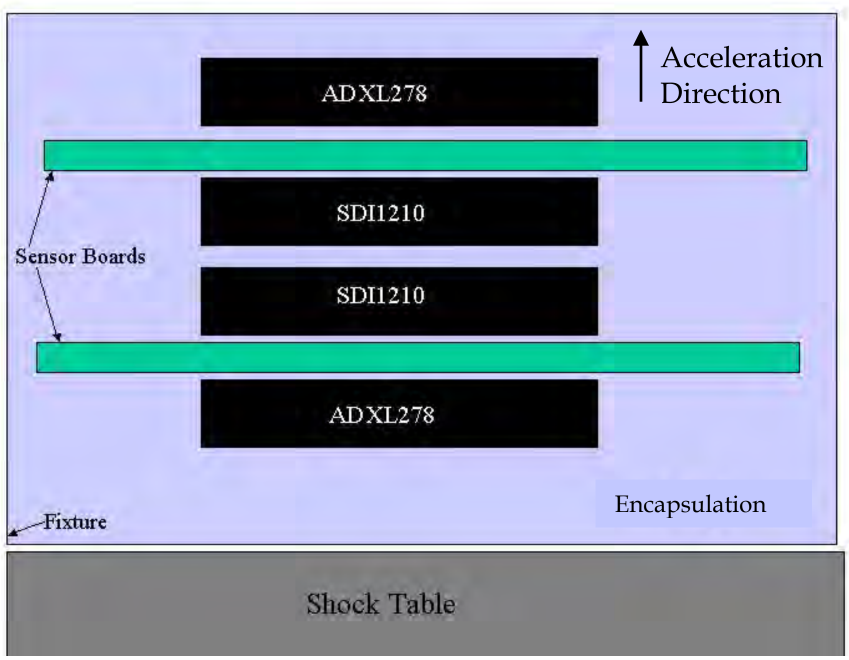

Figure 14. Sketch of ADXL278/SDI1210 Shock Experiment Configuration.

The ADXL278 two-axis accelerometer survived when it was mounted on the top or on the bottom of the board in both the set-back and balloting shock orientations to the maximum 32,000-g shock level. There seemed to be no bias shifts larger than 1 g until the fifth shock experiment at a 30,000-g shock level. It is not known how successive shocks affect the device structure. As a result of this set of experiments, the ADXL278 was recommended for artillery-level flight conditions and was qualified to a 30,000-g shock level.

Table 5. SDI1210 Shock Experiment Results

Shock No.	Max Shock Level (kg)	Sense Axis and Orientation	Shock Table Orientation	Before Shock Bias (V)	After Shock Bias (V)	Δ Bias (V)	Δ Bias (g)	Comments
1	19000	+I Top	+X	2.700	2.700	0.000	0	
		-I Bottom	-X	2.340	2.320	0.020	0.10	
2	16995	+I Top	+X	2.704	2.701	0.003	0.01	
		-I Bottom	-X	2.369	2.159	0.210	1.00	
3	21408	+I Top	+X	2.702	2.681	0.021	0.10	
		-I Bottom	-X	2.148	1.185	0.963	4.59	Large Bias Shift
4	25915	+I Top	+X	2.683	3.409	-0.726	-3.46	Large Bias Shift
		-I Bottom	-X	1.187	0	1.187		Not Operational
5	29999	+I Top	+X	3.432	0	3.432		Not Operational
		-I Bottom	-X	0	0			Not Operational
6	13098	+I Side	+Y	0	0			Not Operational
		-I Side	-Y	0	0			Not Operational
7	32159	+I Side	+Y	0	0			Not Operational
		-I Side	-Y	0	0			Not Operational

Table 6. ADXL278 Shock Experiment Results

Shock No.	Max Shock Level (g)	Sense Axis and Orientation	Shock Table Orientation	Before Shock Bias (V)	After Shock Bias (V)	Δ Bias (V)	Δ Bias (g)	Comments
1	19000	+K Top	+Z	2.500	2.500	0	0	
		-J Top	+Y	2.480	2.480	0	0	
		-K Bottom	-Z	2.490	2.490	0	0	
		+J Bottom	-Y	2.500	2.500	0	0	
2	16995	+K Top	+Z	2.500	2.502	-0.002	-0.07	
		-J Top	+Y	2.480	2.480	0.000	0	
		-K Bottom	-Z	2.489	2.486	0.003	0.10	
		+J Bottom	-Y	2.505	2.514	-0.009	-0.30	
3	21408	+K Top	+Z	2.501	2.519	-0.018	-0.60	
		-J Top	+Y	2.478	2.478	0	0.00	
		-K Bottom	-Z	2.485	2.484	0.001	0.03	
		+J Bottom	-Y	2.511	2.510	0.001	0.03	
4	25915	+K Top	+Z	2.519	2.520	-0.001	-0.03	
		-J Top	+Y	2.478	2.470	0.008	0.27	
		-K Bottom	-Z	2.484	2.470	0.014	0.47	
		+J Bottom	-Y	2.510	2.494	0.016	0.53	
5	29999	+K Top	+Z	2.520	2.518	0.002	0.07	
		-J Top	+Y	2.470	2.469	0.001	0.03	
		-K Bottom	-Z	2.470	2.511	-0.041	-1.37	
		+J Bottom	-Y	2.494	2.498	-0.004	-0.13	
6	13098	+K Side	+X	2.555	2.544	0.011	0.37	
		-J Side	+Y	2.479	2.479	0	0	
		-K Side	-X	2.485	2.484	0.001	0.03	
		+J Side	-Y	2.496	2.496	0	0	
7	32159	+K Side	+X	2.544	2.545	-0.001	-0.03	
		-J Side	+Y	2.479	2.479	0	0	
		-K Side	-X	2.485	2.485	0	0	
		+J Side	-Y	2.496	2.497	-0.001	-0.03	

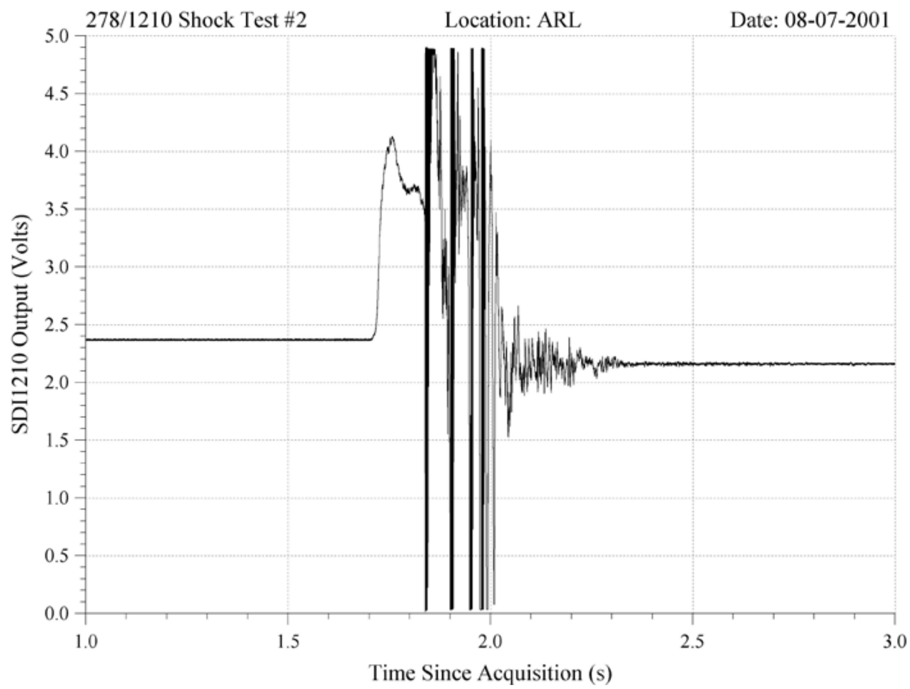

Figure 15. SDI1210 Output (-I-axis bottom) During Shock Experiment No. 2.

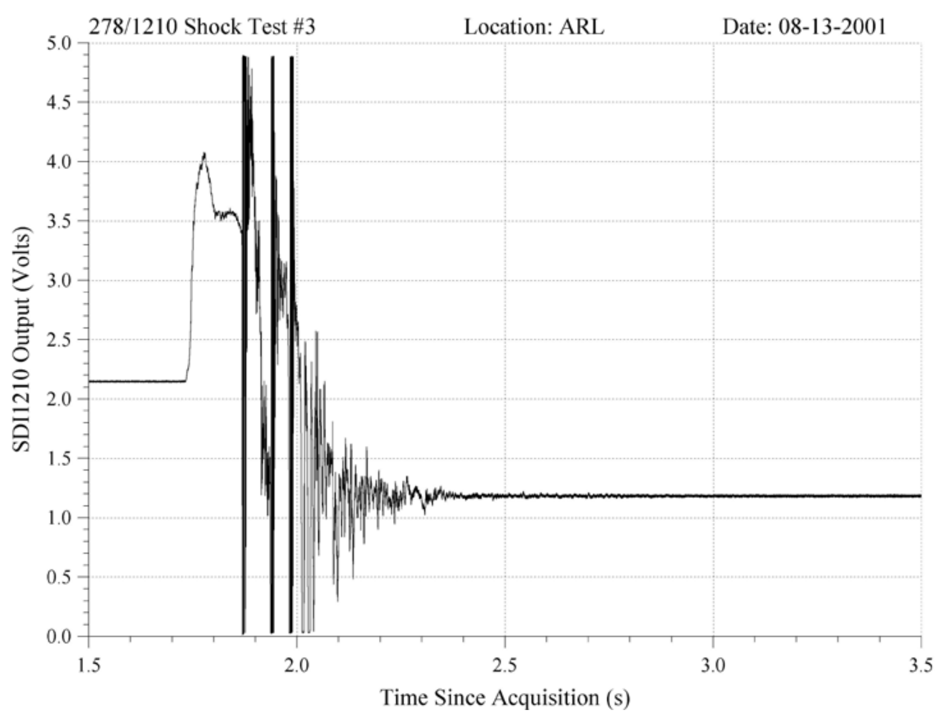

Figure 16. SDI1210 Output (-I-axis bottom) During Shock Experiment No. 3.

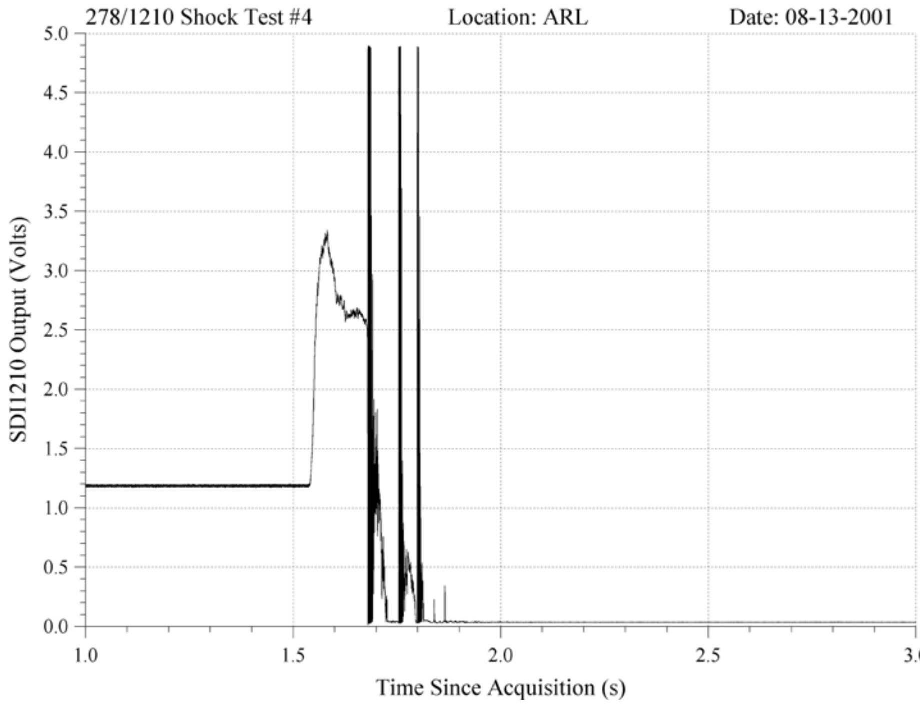

Figure 17. SDI1210 Output (-I-axis bottom) During Shock Experiment No. 4.

4. Conclusions

The results from the shock experiments are summarized as follows: ADXL78 and ADXL278 survived when mounted on the top or bottom of the board after repeated shock accelerations to a 32,000-g magnitude without serious performance degradation; SDI210 survived a 19,000-g shock in the set-back orientation once without scale factor or bias errors and eventually failed after repeated shocks; HMC1023 survived the 13,000-g set-back shock, 15,000-g balloting shock, and 20,000-g set-forward shock; and the ADXL250, when oriented on top of the board, survived a 21,000-g shock but when oriented on the bottom of the board, only survived a set-back acceleration of 14,000 g. The ADXL250 also had performance trouble when shocks occurred in the balloting and set-forward orientation. As a result of these shock experiments, the ISS board was g-qualified to a minimum of 19,000 g if the ADXL278's are used. If the ADXL250's are used instead of the ADXL78's, the g-qualification decreases to at least 14,000 g. Some of the failures occurred when the devices were subjected to extremely high shocks in the balloting and set-forward orientation. These are unlikely to occur in artillery-level launches but are possible for tank or small caliber projectiles. The authors feel that the ISS has a good chance to survive launch conditions exceeding 30,000 g since the set-forward and balloting loads would be estimated to be 6,000 g and 3,000 g, respectively.

The authors feel that the recent shock experiments of the ISS boards have provided an adequate level of g-qualification for a successful evaluation of the current Navy and Army projectiles undergoing development. Recently, DFuzes have been purchased by NSWC for flight experiments in support of the Navy's ERGM, Advanced Gun System, and Autonomous Naval Support Round programs. The harshest of these launch conditions required the DFuze to survive a 15,000-g launch acceleration while powered. Recent flight data from these experiments have shown that the ISS boards survived the high-g launch conditions and transmitted excellent data from each sensor without any performance degradation. To date, 30 ISS boards have been flight tested without any failures. Twenty-five DFuzes were flown on large caliber projectiles and five DFuzes that had been re-configured were flown on small caliber projectiles. If a customer would want to perform a flight experiment exceeding 30,000 g, more realistic air or rail gun ground experimentation could be implemented to verify survivability before flight. DFuzes have also been purchased by the U.S. Army Tank-Automotive and Armaments Command, Armament Research Development and Engineering Center, to support the Army's XM982 Excaliber program.

INTENTIONALLY LEFT BLANK

References

1. Davis, B.S., and D.J. Hepner, *Yawsonde and Microelectromechanical Systems (MEMS) Accelerometer Data of the M898 Sense and Destroy Armor (SADARM) Projectile During Flight Performance Tests (FPTs) II, II, and IV*, ARL-MR-417, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, September 1998.

2. Hepner, D.J., and G. Borgen, *A High-G Flight Experiment of a Field-Programmable Gate Array (FPGA) Pulse Code Modulation (PCM) Encoder*, 46th ISA, Bellvue, WA, May 2000.

3. Burke, L.W., E. Bukowski, C. Newnham, N. Scholey, W. Hoge, and Z. Ye, *HSTSS Battery Development for Missile and Ballistic Telemetry Applications*, ARL-MR-477, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, May 2000.

4. Davis, B.S., J.A. Condon, and T.G. Brown, *Flight Demonstration Results of an Inertial Measurement Unit and Global Positioning System Translator Telemetry System*, ARL-TR-2630, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, November 2001.

5. Muller, P.C., *PCM Encoders – U.S. Army PCM Encoder Development*, HSTSS Symposium, Denver, CO, August 2001.

6. Hepner, D.J., M.S.L. Hollis, and C.E. Mitchell, *Yawsonde Technology for the Jet Propulsion Laboratory (JPL) Free-Flying Magnetometer (FFM) Program*, ARL-TR-1610, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, July 1998.

7. Davis, B.S., T.G. Brown, C.R. Myers, and M.S.L. Hollis, *Ground and Flight Testing of Microelectromechanical Systems (MEMS) Sensors for the Commercial Technology Insertion Program (CTIP)*, ARL-MR-384, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1998.

INTENTIONALLY LEFT BLANK

NO. OF
COPIES ORGANIZATION

1 ADMINISTRATOR
DEFENSE TECHNICAL INFO CENTER
ATTN DTIC OCA
8725 JOHN J KINGMAN RD STE 0944
FT BELVOIR VA 22060-6218

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL CS AI R REC MGMT
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL CI LL TECH LIB
2800 POWDER MILL RD
ADELPHI MD 207830-1197

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL D D SMITH
2800 POWDER MILL RD
ADELPHI MD 20783-1197

4 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR CCF A C ROBINSON
M D'ONOFRIO W KONICK
B CHRISTOPHERSON
2800 POWDER MILL RD
ADELPHI MD 20783-1197

8 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL SE RL M DUBEY
B PIEKARSKI
AMSRL SE S J EIKE
AMSRL SE SA J PRICE
AMSRL SE SS LADAS
A EDELSTEIN D FLIPPEN
AMSRL SE EE Z SZTANKAY
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL WM MB A FRYDMAN
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 US ARMY CECOM RDEC
ATTN AMSEL RD C2 CS J VIG
FORT MONMOUTH NJ 07703-5601

NO. OF
COPIES ORGANIZATION

1 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR QAC M BOMUS
PICATINNY ARSENAL NJ 07806-5000

3 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR FSF T S CHUNG
M AMORUSO
AMSTA AR FSF D C PEREIRA
PICATINNY ARSENAL NJ 07806-5000

6 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR FSP S PEARCY
AMSTA AR FSP G S DEFEO
P GRANGER D CARLUCCI
R WERKO
AMSTA AR FSP E A BAHIA
PICATINNY ARSENAL NJ 07806-5000

2 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR FS A WARNASCH
AMSTA AR FSA K CHIEFA
PICATINNY ARSENAL NJ 07806-5000

5 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR CCH A R CARR
M LUCIANO G KOLASA
M PALATHINGAL D VO
PICATINNY ARSENAL NJ 07806-5000

2 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR CCL B R MAZESKI
D AHMAD
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR RMP N GRAY
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC
ATTN AMSTA AR CCL A E REMFER
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC
ATTN SFAE GCSS BM R KOWALSKI
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC
ATTN SFAE GCSS ARMS C GRASSANO
PICATINNY ARSENAL NJ 07806-5000

1 DARPA/MTO
ATTN W TANG
3701 N FAIRFAX DRIVE
ARLINGTON VA 22203-1714

NO. OF
COPIES ORGANIZATION

8 CDR NAVAL SURF WARFARE CTR
ATTN G33 J FRAYSSE G32 ELLIS
G34 H WENDT M HAMILTON
G61 LARACH D HAGEN
A EVANS B52 M ABAIE
17320 DAHLGREN ROAD
DAHLGREN VA 22448-5100

7 CDR NAVAL SURF WARFARE CTR
INDIAN HEAD DIV
ATTN CODE 40P3 D GARVICK
CODE 4420F L FAN
CODE 4110C K JOHNSON
CODE 433 V CARLSON
CODE 4420 P SMITH
CODE 4120 M. WILMOTH
CODE 410A C PARAS
101 STRAUSS AVE
INDIAN HEAD MD 20640-5035

1 CDR NAVAL SURF WARFARE CTR
DAHLGREN DIV
ATTN CODE 40D J BLANKENSHIP
6703 WEST HIGHWAY 98
PANAMA CITY FL 32407-7001

1 IDA
SCIENCE AND TECH DIV
ATTN H LAST
1801 N BEAUREGARD ST
ALEXANDRIA VA 22311-1772

2 CDR OFC OF NAVAL RSCH
ATTN CODE 333 J GOLDWASSER
P MORRISSON
800 N QUINCY ST RM 507
ARLINGTON VA 22217-5660

1 CDR AFRL/MNMF
ATTN S ROBERSON
306 W EGLIN BLVD STE 219
EGLIN AFB FL 32542-6810

2 CDR NAWC WEAPONS DIV
ATTN G BORGEN D POWELL
CODE 543200E BLDG 311
POINT MUGU CA 93042-5000

3 CDR NAVAL AIR WARFARE CTR
WEAPONS DIVISION
ATTN CODE C3923 S GATTIS
CODE C3904 D SCOFIELD
S MEYERS
CHINA LAKE CA 93555-6100

NO. OF
COPIES ORGANIZATION

4 PROGRAM MANAGER ITTS
STRICOM
ATTN AMFTI EL D SCHNEIDER
R COLANGELO
R CARPENTER
C GOODWIN
12350 RESEARCH PKWY
ORLANDO FL 32826-3276

1 DIRECTOR
US ARMY RTTC
ATTN STERT TE F TD R EPPS
REDSTONE ARSENAL AL 35898-8052

1 CDR US ARMY
YUMA PROVING GROUND
ATTN STEYP MT AT A A HOOPER
YPG AZ 85365-9110

10 CDR US ARMY AMCOM
ATTN AMSAM RD MG NC P RUFFIN
J BAEDER V LEFEVRE
AMSAM RD MG IP G HUTCHESON
AMSAM RD WS DP TD S BURGETT
C LEWIS C ROBERTS
B ROBERTSON
AMSAM RD WS ID P ASHLEY
T HUDSON
REDSTONE ARSENAL AL 35898-5247

1 TEST ARTICLE PREP DEP
NAWCAD CODE 540000A R FAULSTICH
BLDG 1492 UNIT 1
PATUXENT MD 20670-1456

1 CDR US ARMY
ATTN STEYP TD ATO A HART
YPG AZ 85365-9106

1 ARROW TECH ASSOCIATES
ATTN W HATHAWAY
1233 SHELBURNE RD STE 8
SOUTH BURLINGTON VT 05403

1 ALLIANT DEFENSE
ATTN A GAUZENS
PO BOX 4648
CLEARWATER FL 33758-4648

1 LOCKHEED/MARTIN-SANDERS
ATTN M CARLSON
NCA1-2078 95 CANAL ST
NASHUA NH 03061-0868

NO. OF COPIES	ORGANIZATION
2	ALLIANT TECHSYSTEMS ATTN C CANDLAND R DOHRN 600 SECOND ST NE HOPKINS MN 55343-8384
2	SAIC ATTN J DISHON G PHILLIPS 16701 W BERNARDO DR SAN DIEGO CA 92127
1	SAIC ATTN J GLISH 8500 NORMANDALE LAKE BLVD SUITE 1610 BLOOMINGTON MN 55437-3828
1	SAIC ATTN M PALMER 1410 SPRING HILL RD STE 400 MCLEAN VA 22102
1	SYSTEMS PLANNING CORP ATTN M MOSES 1429 QUINCY ST ARLINGTON VA 22207
2	ROCKWELL COLLINS ATTN M JOHNSON R MINOR 350 COLLINS RD NE CEDAR RAPIDS IA 52498
1	SWALES AEROSPACE ATTN Q LAM 5050 POWDER MILL RD BELTSVILLE MD 20705
1	UCLA ATTN J JUDY 68 –121 ENGINEERING IV BOX 951594 LOS ANGELES CA 90095-1594
1	JOHNS HOPKINS UNIV APPLIED PHYSICS LABORATORY ATTN W D'AMICO 1110 JOHNS HOPKINS RD LAUREL MD 20723-6099
5	CHLS STARK DRAPER LAB ATTN J CONNELLY J SITOMER R POLUTCHKO T EASTERLY A KOUREPENIS F HARRISON 555 TECHNOLOGY SQUARE CAMBRIDGE MA 02139-3563

NO. OF COPIES	ORGANIZATION
1	UC BERKELEY ATTN A PISANO DEPT OF MECH ENG 5101-B ETCHEVERRY HALL BERKELEY CA 94720-1740
1	SUNY ATTN R MARCHAND DEPT OF MATHEMATICS & COMPUTER SCIENCE FREDONIA NY 14063
3	GEORGIA TECH RSCH INST COBB CO RSCH FACILITY ATTN J MCMICHAEL A LOVAS D PAREKH 7220 RICHARDSON RD SMYRNA GA 30080
1	GEORGIA INST OF TECH SCOOL OF AEROSPACE ENG ATTN A CALISE 270 FERST DR ATLANTA GA 30332-0150
2	ANALOG DEVICES ATTN B SULOFF S LEWIS 21 OSBORN ST CAMBRIDGE MA 02139-3556
1	ANALOG DEVICES ATTN R MEISENHELDER 804 WOBURN ST WILMINGTON MA 01887-3462
1	HONEYWELL ATTN MN14-3B35 M CARUSO 12001 STATE HIGHWAY 55 PLYMOUTH MN 55441
1	AEROVIRONMENT ATTN C MIRALLES 4685-3H INDUSTRIAL ST SIMI VALLEY CA 93063
1	ROCKWELL SCIENCE CTR ATTN I GOLDBERG PO BOX 1085 THOUSAND OAKS CA 91358
1	SILICON DESIGNS ATTN J COLE 1445 NW MALL ST ISSAQUAH WA 98027

NO. OF COPIES	ORGANIZATION
1	CDR NAVSEA ATTN M SIMMS CODE 6024 BLDG 2940W CRANE IN 47522

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
2	DIRECTOR US ARMY RESEARCH LABORATORY ATTN AMSRL CI LP (TECH LIB) BLDG 305
2	DIR USARL ATTN AMSRL WM T ROSENBERGER AMSRL WM B A HORST BLDG 4600
10	DIR USARL ATTN AMSRL WM BA D LYON J CONDON B DAVIS T HARKINS D HEPNER G KATULKA D LYON P MULLER P PEREGINO A THOMPSON T BROWN BLDG 4600
6	DIR USARL ATTN AMSRL WM BC P PLOSTINS J GARNER B GUIDOS J NEWILL P WEINACHT J DESPIRITO BLDG 390
3	DIR USARL AMSRL WM BF J LACETERA H EDGE T HAUG BLDG 390
2	DIR USARL AMSRL WM RP C SHOEMAKER J BORNSTEIN BLDG 1121
2	DIR USARL ATTN AMSRL WM MB C HOPPEL ATTN AMSRL WM MC R ADLER BLDG 4600
6	DIR USARL ATTN AMSRL WM T B BURNS ATTN AMSRL WM TC R COATES W DEROSSET R MUDD AMSRL WM TD F GREGORY N GNIAZOWSKI BLDG 309
4	CDR US ARMAMENT RD&E CTR ATTN AMSTA AR FST T R LIESKE J WHITESIDE J MATTS F MIRABELLE BLDG 120
1	CMDR USA DTC ATTN CSTE DTC TTM J SCHNELL RYAN BLDG
1	CDR ATC ATTN K MCMULLEN BLDG 359

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2002	Final

4. TITLE AND SUBTITLE
Shock Experiment Results of the DFuze 8-Channel Inertial Sensor Suite That Contains Commercial Magnetometers and Accelerometers

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
Davis, B.S. (ARL); Hamilton, M.B. (NSWC); Hepner, D.J. (ARL)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Weapons & Materials Research Directorate
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Weapons & Materials Research Directorate
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-MR-532

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes shock experiments performed on a 1.4-inch (35.56-mm) diameter double-sided board that contains an inertial sensor suite (ISS) in support of the ongoing U.S. Army Research Laboratory diagnostic fuze (DFuze). The DFuze represents a high-g projectile-borne measurement system for obtaining in-bore and in-flight ballistic data that significantly contribute toward the design, development, failure diagnostics, and aerodynamics determination of artillery or other projectiles. The ISS uses several commercial off-the-shelf micro-electro-mechanical systems accelerometers, magnetometers, and optical sensors used for determining estimates of the projectile's body orientation, axial acceleration, radial acceleration, and roll rate. During the ground experiments, ISS boards were encapsulated within a specially designed fixture and shocked while powered in various orientations to simulate high-g set-back, set-forward, and balloting launch conditions. Post-shock performance of each sensor was then obtained to determine bias offset, scale factor errors, and shock survivability. The shock experiments were performed on a high velocity and acceleration shock machine at Aberdeen Proving Ground, Maryland. As a result of these experiments, the ISS boards have been g-qualified to at least a 19-kg launch acceleration while powered. The ISS boards will be used in ongoing DFuze flight experiments in support of the following Navy and Army developmental projectile programs: Extended Range Guided Munitions, Advanced Gun System, Autonomous Naval Support Round, XM982 Excaliber, and Tank Extended Range Munition Kinetic Energy XM1007. To date, 30 ISS boards have been flight tested without any failures.

14. SUBJECT TERMS
accelerometer, inertial measurement unit, shock tests, high-g acceleration, sensors

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102